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MAGSONDE: A Device for Making Angular Measurements on Spinning Projectiles With Magnetic Sensors

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Abstract

Accurate measurement of angular motion of spinning bodies with on-board sensors has long been recognized as a daunting task. Recent advances in magnetic sensor technologies have yielded devices small enough, rugged enough, and sensitive enough to be useful in systems that make high-speed, high-resolution measurements of attitude relative to magnetic fields when these sensors are installed on free-flying bodies.

Such a measurement system, called a "MAGSONDE" (MAGnetic SONDE), has been designed for use in spinning projectiles for the estimation of in-flight angular orientation with respect to the earth's magnetic field. The MAGSONDE is comprised of both an apparatus and a methodology that determine orientation from sensor phase measurements. Sensor scale factor variations will not affect MAGSONDE performance. Other significant features of the MAGSONDE are its day/night and all-weather capability and its use of non-emissive, passive sensors. Potential applications for MAGSONDE include (but are not limited to) navigational aids and determination of angular motion histories of experimental, developmental, and tactical projectiles.

ACKNOWLEDGMENTS

Mr. Brad Davis of the Weapons and Materials Research Directorate (WMRD) of the U.S. Army Research Laboratory (ARL) has been the lead engineer for the magnetic sensor experiments performed at ARL. His efforts have greatly aided the authors in their appreciation of the potential of magnetic sensors. He is an integral part of the team pursuing engineering development of the MAGSONDE. He has also reviewed this report. Ms Rachel Harkins' assistance in document preparation is also gratefully recognized.

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1. Introduction

Recent advances in magnetic sensor technologies have resulted in devices small enough, rugged enough, and sensitive enough to be useful in systems capable of making high-speed, high-resolution measurements of attitude relative to magnetic fields when these sensors are installed on free-flying bodies. This report provides the analytical support for such a measurement system, called a "MAGSONDE" (MAGnetic SONDE), which employs fixed magnetic sensor(s) on a rotating body for the estimation of that body's orientation with respect to a stationary magnetic field. An application of particular interest to the Army is measurement of in-flight angular orientation of spinning projectiles with respect to the earth's magnetic field.

Although devices responsive to the earth's magnetic field have long been used for heading estimation, MAGSONDE is a new and unique technology. It differs from all other known systems that give orientations with respect to a magnetic field in that those systems use one or more of four basic measurement types to determine orientations: 1) field strength along a sensor axis, 2) relative field strength along multiple sensor axes, 3) rate of change of field strength along a sensor axis, and 4) relative rates of change along multiple sensor axes. In every case, the measurements are premised on some evaluation of a component of the magnetic field along a sensor axis and require prior knowledge of the field and/or accurate sensitivity calibration. Making angular measurements with MAGSONDE only requires the magnetic sensor(s) to identify the times when there is no magnetic field along the sensor axis. In this case, the measurements are premised on the absence of a magnetic field component along a sensor axis. MAGSONDE determines orientation from relative phase information in the sensor output at zero crossings and is therefore independent of amplitude. This feature is important for several reasons: 1) No knowledge of the field strength is required, 2) manufacturing tolerances that affect sensitivity have no impact on orientation determination, and 3) only scalar arithmetical operations are required for the angular measurements.

Potential applications for MAGSONDEs include (but are not limited to) navigational aids and determination of angular motion histories of experimental, developmental, and tactical projectiles. The processed sensor data can be used as a diagnostic tool for aerodynamic performance, projectile-payload interactions,

[1]patent pending

projectile-weapon interactions, determination of maneuver authority for guided munitions, and as a navigational aid for "jammed" global positioning system (GPS)-fitted munitions. The sensor data can also provide a relative roll orientation and roll rate reference for calibrating ancillary data sources such as accelerometers and angular rate sensors.

A SOLARSONDE, commonly called "yawsonde," is a similar sensor-based angular measurement capability that uses sunlight as a reference field. It is widely used in many projectile study programs for in-flight measurements of the solar aspect angle, which is defined as the angle between a spinning projectile's axis of rotation and a vector from the center of gravity (CG) to the sun. MAGSONDE systems are in many ways analogous to SOLARSONDE. However, there are four important distinctions: outer surface access, launch window, bias sensitivity, and frequency response. The main disadvantages of a SOLARSONDE are the requirement for access to the exterior surface of a rotating body and the dependence on an unobscured solar line of sight. Given that an observable measurement is possible, the internally mounted magnetic sensors of a MAGSONDE have the advantage of an unchanging magnetic launch window suitable for day/night and all-weather conditions. For some projectile orientations, the converse argument for the SOLARSONDE is that as time passes, the daily variation in the solar vector will always ensure an observable solar angle measurement, while the unchanging magnetic field may not ever yield a measurement. The current SOLARSONDE has no bias or frequency response susceptibility, either of which can drastically change the derived angular measurement from a MAGSONDE. Thus, the MAGSONDE has a stringent signal-conditioning and instrumentation calibration requirement.

A complete MAGSONDE system includes the sensor design and qualification, a multiple sensor application, calibration, launch window simulation, successful acquisition of flight data, and data processing. Each of these aspects is discussed in sequence.

2. Sensor Design and Qualification

A fundamental MAGSONDE requirement is that projectile spin rotates the sensor(s) in a stationary magnetic field. The sensor(s) must have a nearly flat frequency response with minimal phase shift over a frequency range to at least two times the roll rate of the body to which it is fitted. A magnetometer suitable for a MAGSONDE must also have a direct current (DC) response characteristic to the magnetic field. For the epicyclic motion typical of spinning projectiles, the processing of the sensor data for MAGSONDE is straightforward when the spin rates are much greater than the precession and nutation rates. When this

condition is not met, more advanced processing algorithms are employed with comparable results.

The MAGSONDE system makes only a single demand of its magnetic sensors, namely, the identification of zero output. Thus, material sensitivity variations, field strength variations, and attenuating flight body materials will have no effect on MAGSONDE performance. Given existing materials responsive to the desired range of magnetic field strength, a sensing device with a favorable signal-to-noise ratio is readily achievable. However, units with built-in electronics must provide both a stable scale factor (gain) and bias (offset) characteristics.

Finally, for military applications, the sensor must be small and rugged and must consume very little power. Devices of this nature are currently being developed by the Defense Advanced Research Program Agency (DARPA). Investigation of their applicability to MAGSONDE is a main consideration for the development, experimentation, and final vendor selection for particular military applications. While the sensor selection is significant, a listing and evaluation of candidate devices is beyond the scope of this report and would needlessly date the otherwise time-independent content.

Within a magnetic field, the flux line through any point can be described by a vector, $\vec{M}$, resolvable into orthogonal components. Without the loss of generality, a system (I, J, K) can be defined so that $\vec{M}$ is in the I-K plane (see Figure 1). The angle between $\vec{M}$ and the +I axis is designated as σ_M. The components of $\vec{M}$ in the I, J, K system are then given by

$$
\begin{aligned}
M_I &= |\vec{M}|\cos(\sigma_M) \\
M_J &= 0 \\
M_K &= |\vec{M}|\sin(\sigma_M)
\end{aligned}
\tag{1}
$$

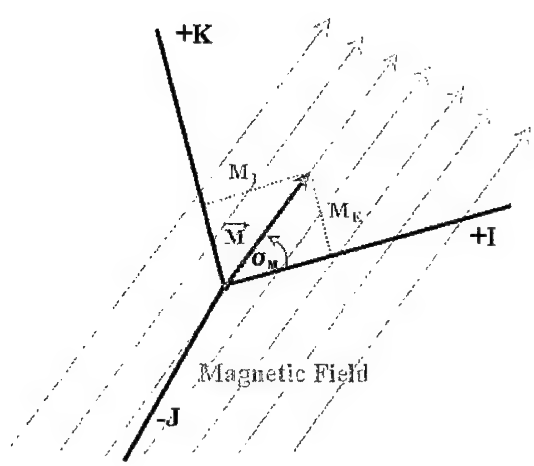


Figure 1. Magnetic Field Through a Point.

The derivation of magnetic attitude is accomplished in MAGSONDE by the evaluation of the output from a pair of rotating sensors crossing the magnetic field. Consider a spinning projectile with its CG at the origin of the I, J, K system, its axis of rotation on the I axis, and its nose pointed in the +I direction (see Figure 2). On board this projectile is a magnetic sensor (S) situated so that its sensitive axis is coplanar with the projectile's spin axis and oriented at a non-zero angle λ (called the tilt angle) from the spin axis. If the projectile roll angle (ϕ_S) is indexed so that the sensor axis lies in the half-plane containing the +J axis and the I axis when the roll angle is zero, the field strength along the sensor axis at any instant is given by

$$\begin{aligned} M_S &= \cos(\lambda) M_I + \sin(\lambda) M_K \sin(\phi_S) \\ &= \cos(\lambda)\left|\vec{M}\right| \cos(\sigma_M) + \sin(\lambda)\left|\vec{M}\right| \sin(\sigma_M)\sin(\phi_S) \end{aligned} \tag{2}$$

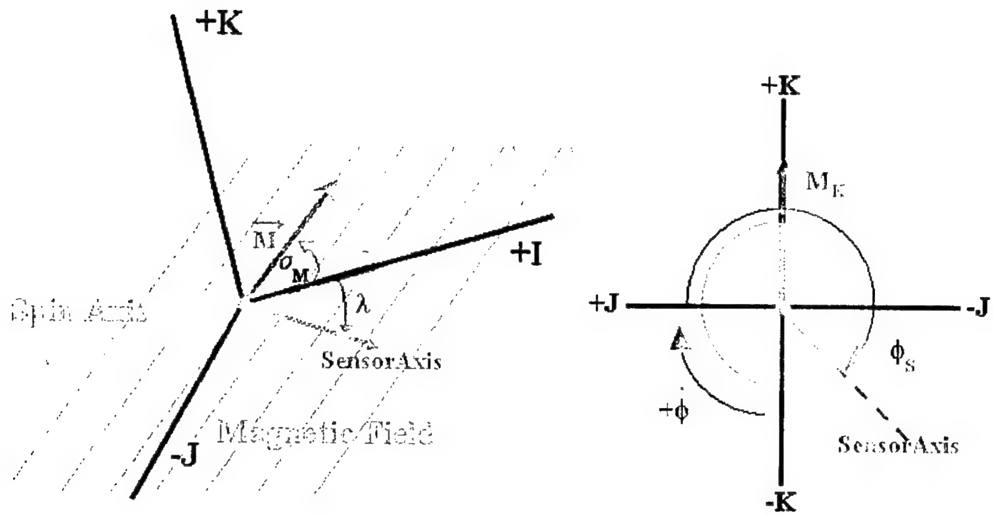


Figure 2. Geometry of Projectile-Borne Magnetic Sensors.

The field strength along a sensor axis, when described with respect to the body-fixed system, has two basic types of contributing terms: an axial (bias) component, $\cos(\lambda)\left|\vec{M}\right|\cos(\sigma_M)$, and a radial (usually roll-modulated) component, $\sin(\lambda)\left|\vec{M}\right|\sin(\sigma_M)\sin(\phi_S)$.

When λ = 90, there is no axial component and Equation 2 simplifies to

$$M_S = \left|\vec{M}\right| \sin(\sigma_M)\sin(\phi_S) \tag{3}$$

Whenever the sensor axis is orthogonal to the field, $M_S = 0$. Two possibilities exist; either $\sin(\sigma_M) = 0$ or $\sin(\phi_S) = 0$. In the first case, $\sigma_M = 0°$ or $\sigma_M = 180°$, the axis of rotation is parallel to the magnetic field, and the field strength is

invariant throughout a roll cycle. In the latter case, $\sin(\sigma_M) \neq 0$, the variation of field strength along the sensor axis is sinusoidal, and $M_S = 0$ when $\phi_S = 0°$ and $180°$.

When $\lambda \neq 90°$, solving Equation 2 for the roll angles at which $M_S = 0$ yields

$$\sin(\phi_S) = \left(\frac{-\cos(\sigma_M)\cos(\lambda)}{\sin(\sigma_M)\sin(\lambda)} \right) \tag{4}$$

The existence criterion for ϕ_S to be a real number of

$$\left| \frac{-\cos(\sigma_M)\cos(\lambda)}{\sin(\sigma_M)\sin(\lambda)} \right| \leq 1$$

leads to the requirement that $90 - \lambda \leq \sigma_M \leq 90 + \lambda$ for the occurrence of an orthogonal condition. This is discussed further in Section 5.

3. A Multiple Sensor Application

Although MAGSONDE style measurements can be made with a single sensor, a two-sensor application is better suited for projectiles that are possibly undergoing complex in-flight kinematics. In Figure 3, two sensors are installed in an artillery fuze body so that their sensitive axes and the axis of rotation of the fuze are co-planar. The sensor tilt angles (λs) are 90° and 60°, respectively.

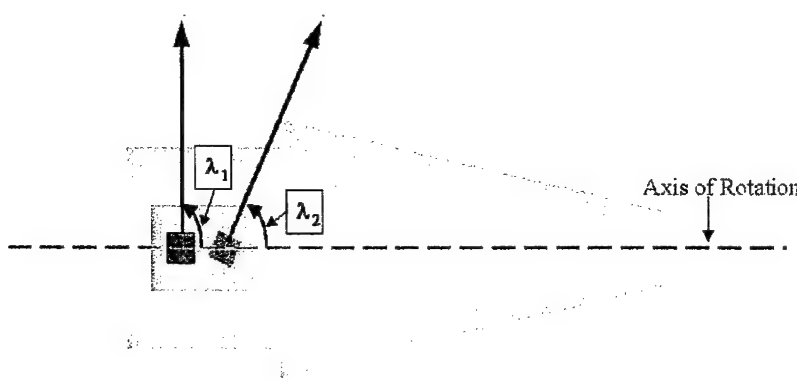


Figure 3. A Fuze-configured MAGSONDE With Two Sensors.

Figure 4 shows the normalized field strength along the sensitive axis for these sensors throughout several roll cycles when the angle between the axis of rotation and the magnetic field (σ_M) is 45°. The critical observation to be made about these curves is that the roll angles at which each of the sensors is

orthogonal to the field, i.e., the zero crossings, are irregularly spaced throughout a roll cycle for $\lambda_2 = 60°$.

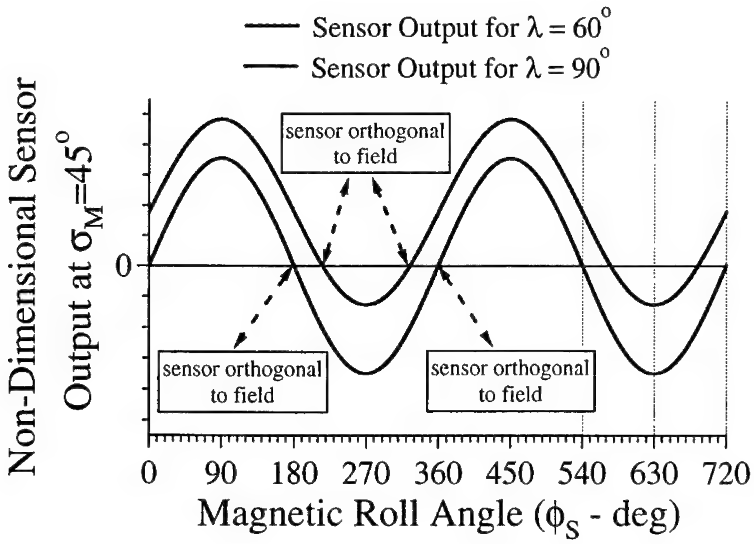


Figure 4. Normalized Magnetic Field Strength Along Sensor Axes.

It was seen in Equations 3 and 4 that, given any fixed tilt angle (λ), the roll angle at orthogonality (ϕ_S) is a function of σ_M. This relationship is plotted in Figure 5 for two sensors with tilt angles of 90° and 60°, as in Figure 3. As previously noted, the zero crossings for a radially oriented sensor, (λ = 90 °), are at roll angles of 0° and 180° for all $\sigma_M \neq 0°$ or $180°$. If $\sigma_M = 0°$ or $180°$, the projectile spin axis is parallel to the magnetic field, and a radially oriented sensor would be orthogonal to the field at all roll angles. For the 60° tilted sensor, the zero crossings are also at roll angles of 0° and 180° for $\sigma_M = 90°$. For other values of σ_M, a phase shift of the zero crossings results, the magnitude of which varies directly with $|\sigma_M - 90|$.

Denoting the two sensors as S_1 (90°) and S_2 (60°) and the two pairs of roll angles at the zero crossings for these sensors as ($\phi_{S_{1A}}, \phi_{S_{1B}}$) and ($\phi_{S_{2A}}, \phi_{S_{2B}}$), the ratio

$$\Phi = \left| \frac{\phi_{S_{2B}} - \phi_{S_{2A}}}{\phi_{S_{1B}} - \phi_{S_{1A}}} \right|$$

is formed (see Figure 6). Also included are similar ratios for sensors, S_2, with tilt angles of 45° and 75°. The ambiguity arising from the symmetry of this ratio about $\sigma_M = 90°$ is easily resolved by checking the parity of the field along S_1 when S_2 is orthogonal to the field. Thus, the combination of the ratio, Φ, and a parity check completely specifies the angle between the projectile axis and the magnetic field. This discriminant can likewise be generated for any two magnetic

sensors with unequal, non-supplementary tilt angles. The choice of sensor orientations in the preceding discussion was made to simplify the algebra, but the number of sensors and sensor orientations in any application could be tailored to meet particular requirements.

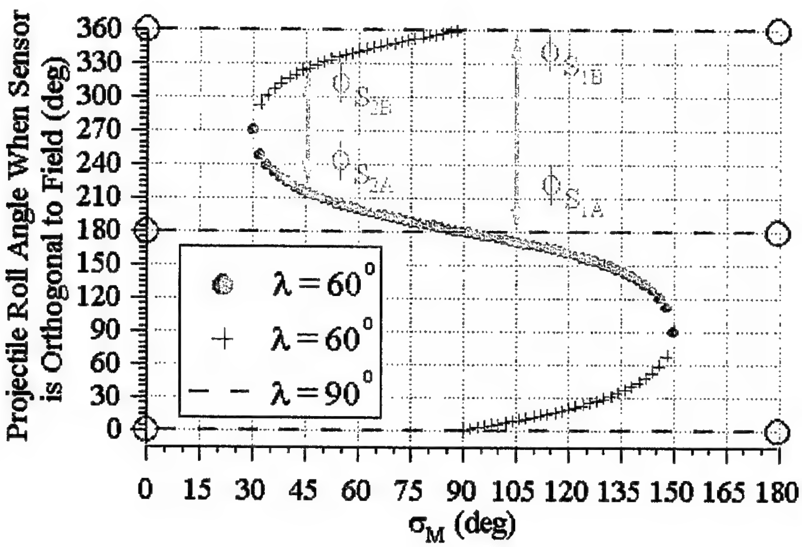


Figure 5. Roll Angle at Orthogonality for Two Sensor Orientations.

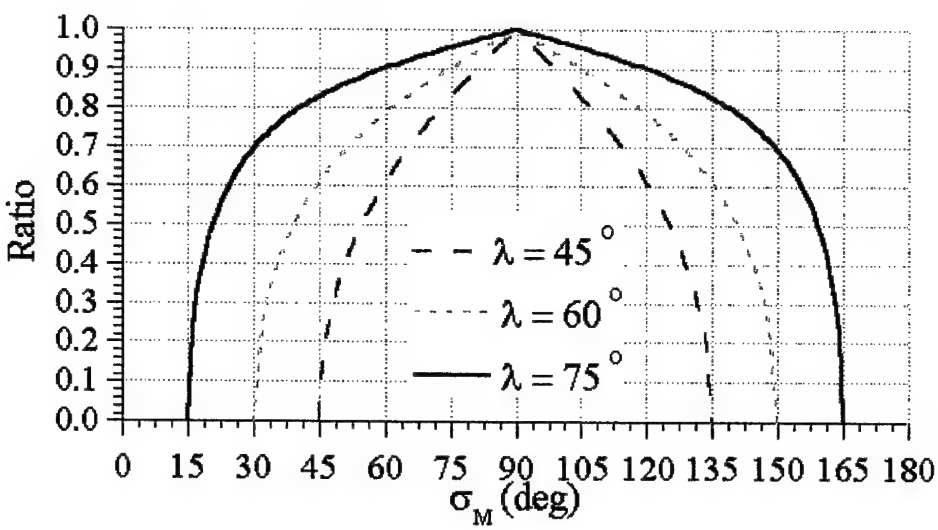


Figure 6. Ratio (Φ) Versus Magnetic Aspect Angle (σ_M) for Three Sensor Orientations (λ).

4. Installation and Calibration

Because of tolerances in the manufacturing and installing of the sensors, the actual orientations of the sensors on a flight body will differ from their designed orientations. These differences in turn will result in different values of the ratio Φ for given values of σ_M. Calibration of each MAGSONDE system after sensor installation will be accomplished with a magnetic field generator and a 2-degree-of-freedom rotary table. The flight body will be installed on a fixture that allows changing angular orientation with respect to the magnetic field in both roll (ϕ_S) and heading (σ_M). Roll positions at orthogonality versus σ_M will be tabulated, and the corresponding ratios will be generated. The tabulated data can be fitted via linear least squares to determine the installed circumferential location and tilt angle of the magnetometer sensitive axis, thus reducing the calibration to two parameters per sensor.

5. Launch Window Simulation

The necessity of each of the magnetic sensors being orthogonal to the field during a roll cycle defines the range of magnetic aspect angles within which a MAGSONDE with a particular sensor configuration is able to operate. This region of applicability is called the MAGSONDE window. As stated in Section 2, a sensor with a tilt angle λ will be orthogonal to the field if and when the roll angle is a solution of

$$\phi_S = \sin^{-1}\left(\frac{-\cos(\sigma_M)\cos(\lambda)}{\sin(\sigma_M)\sin(\lambda)}\right).$$

The existence criterion for ϕ_S of

$$\left|\frac{-\cos(\sigma_M)\cos(\lambda)}{\sin(\sigma_M)\sin(\lambda)}\right| \leq 1$$

leads to the requirement that $90-\lambda \leq \sigma_M \leq 90+\lambda$.

The suitability of a MAGSONDE system for a particular flight depends of the range of possible magnetic headings (σ_Ms) during that flight. Given the direction of the earth's magnetic field at the flight location and an estimate of the anticipated trajectory, possible sensor packages and lines of fire that result in good geometry can be determined.

Although the earth's magnetic field varies with both location and time, these variations are regular and known. Moreover, the variations over the length and

duration of a projectile trajectory are typically negligible, excluding local anomalies. Thus, given knowledge of the flight location, the magnetic field near the earth's surface can be obtained from geodetic survey data, computer models, or direct measurement.

Simulated trajectory data are then used to estimate the nominal anticipated magnetic heading angle history. In some cases, it will be true that for a portion of the trajectory, the body's attitude with respect to the magnetic field is inside the MAGSONDE measurement capability sometimes and outside that capability at other times. For applications in which limited portions of a flight are of interest, MAGSONDE coverage at only those times need be guaranteed.

6. Acquisition of Flight Data

Raw sensor data can either be stored on board and recovered or be transmitted to a ground station. Two methods of data collections can be used for telemetry applications: analog data via FM/FM or digital data via pulse code modulation (PCM). Analog applications include FM/FM telemetry via high frequency voltage-controlled oscillators. Digital applications would primarily use on-board PCM systems to digitize and serialize the data for common telemetry practices. Typical reduction techniques employing non-causal, digital filtering and curve fitting would be used to determine the occurrence of orthogonality (i.e., zero crossings of the signal).

7. Data Processing

Whatever acquisition and processing techniques are employed, the objective is to tabulate a temporal history of three data at each of the zero crossings during the flight: the sensor identification (1 or 2), the time of the crossing, and the polarity of the other sensor at that time. With these data, a standard methodology for extracting magnetic aspect angle and roll rate is presented. All available data will be collected and archived and can be reduced in the field environment to provide feedback during an experiment and enhance the flexibility of the study requirements. Advanced reduction techniques can be substituted when appropriate, including (but not limited to) compensation for rapid changes in magnetic aspect angle or roll rate.

7.1 Magnetic Aspect Angle Measurement

In Sections 2 and 3, the value of the ratio

$$\Phi = \left| \frac{\phi_{S_{2B}} - \phi_{S_{2A}}}{\phi_{S_{1B}} - \phi_{S_{1A}}} \right|$$

combined with the polarity of S_1 when S_2=0 was shown to uniquely specify σ_M. Flight data will not give sensor roll angles at zero crossings but times when these crossings occurred. If two constraints are present, the crossing times can also be used to directly compute σ_M. These constraints are

The magnetic roll rate is constant for four consecutive zero crossings; and

σ_M is constant for these four crossings.

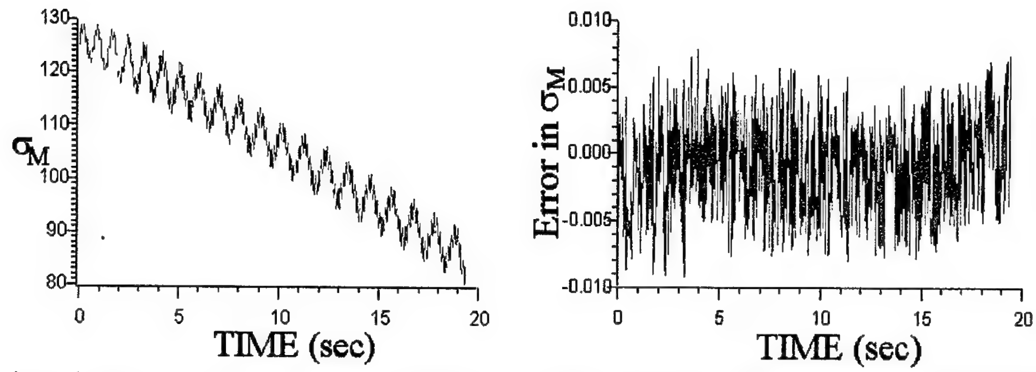
With these two restrictions, the magnetic roll acceleration, roll rate, roll position, and ratio of four consecutive sensor occurrences in the sequence $S_{1_A}, S_{2_A}, S_{2_B}, S_{1_B}$ are given by

$$\begin{aligned} \ddot{\phi}_{S_{1A},S_{2A},S_{2B},S_{1B}} &= 0 \\ \dot{\phi}_{S_{1A},S_{2A},S_{2B},S_{1B}} &= a_1 \\ \phi_{S_{1A},S_{2A},S_{2B},S_{1B}} &= a_0 + a_1 t_{S_{1A},S_{2A},S_{2B},S_{1B}} \end{aligned} \tag{5}$$

$$\Phi = \left| \frac{\phi_{S_{2B}} - \phi_{S_{2A}}}{\phi_{S_{1B}} - \phi_{S_{1A}}} \right| = \left| \frac{\left(a_0 + a_1 t_{S_{2B}}\right) - \left(a_0 + a_1 t_{S_{2A}}\right)}{\left(a_0 + a_1 t_{S_{1B}}\right) - \left(a_0 + a_1 t_{S_{1A}}\right)} \right| = \left| \frac{t_{S_{2B}} - t_{S_{2A}}}{t_{S_{1B}} - t_{S_{1A}}} \right| \tag{6}$$

Thus, Φ computed from zero crossing times is the same as that computed from roll position calibration data at any constant σ_M.

In flight, these constraints are seldom true, but for simulated flights of several types of projectiles, the differences between Φ computed from in-flight crossing times with the standard methodology and Φ from calibration only resulted in errors in σ_M estimates on the order of hundredths of degrees. A representative example is seen in Figure 7 where the σ_M history for a simulated trajectory of an M483A1 artillery projectile at the transonic range at Aberdeen Proving Ground and the errors in the σ_M estimates are given. In these simulations, noiseless sensors and 64-bit precision were assumed.



a) σ_M history during simulated flight   b) Error in σ_M estimates with MAGSONDE

Figure 7. Errors in σ_M Estimates Attributable to Violation of Standard Reduction Assumptions in a Simulated Flight.

7.2 Magnetic Roll Rate Measurement

The standard reduction estimates magnetic roll rate by numerically differentiating the magnetic roll position history. The calibrated roll positions $\left(\phi_{S_{1A_1}}, \phi_{S_{2A_1}}, \phi_{S_{2B_1}}, \phi_{S_{1B_1}}, \phi_{S_{1A_2}}, \phi_{S_{2A_2}}, \phi_{S_{2B_2}}, \phi_{S_{1B_2}}, \ldots\right)$ for each of the zero crossing times and magnetic aspect angles are assigned. Using the sensor identification in the flight data, one can determine a temporal history of the sensor's roll positions. This crossing times history is used to estimate the roll rate. When σ_M is near 90° and/or when the yaw and pitch rates are relatively low compared to the roll rate, magnetic roll rate and the body's spin rate are equivalent.

8. Conclusions

A methodology for deriving the heading and the roll rate of a spinning projectile relative to a magnetic field has been formulated. Devices employing this methodology, called "MAGSONDEs," are currently in engineering development. It is planned to include MAGSONDEs in flight study programs in the near future. MAGSONDEs will provide an all-weather, day/night angular measurement capability for spinning projectiles that does not currently exist.

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13. ABSTRACT *(Maximum 200 words)*

Accurate measurement of angular motion of spinning bodies with on-board sensors has long been recognized as a daunting task. Recent advances in magnetic sensor technologies have yielded devices small enough, rugged enough, and sensitive enough to be useful in systems that make high-speed, high-resolution measurements of attitude relative to magnetic fields when these sensors are installed on free-flying bodies.

Such a measurement system, called a "MAGSONDE" (MAGnetic SONDE), has been designed for use in spinning projectiles for the estimation of in-flight angular orientation with respect to the earth's magnetic field. The MAGSONDE is comprised of both an apparatus and a methodology that determine orientation from sensor phase measurements. Sensor scale factor variations will not affect MAGSONDE performance. Other significant features of MAGSONDE are its day/night and all-weather capability and its use of non-emissive, passive sensors. Potential applications for MAGSONDE include (but are not limited to) navigational aids and determination of angular motion histories of experimental, developmental, and tactical projectiles.

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